Unification of all blazars

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Abstract: The overall spectra (SED) of blazars, from radio to γ–ray energies, seem to obey well defined trends, with a continuity of properties between blazars of different classes. To quantify this statement we can either investigate their *observed* properties (see Fossati et al., this volume), or try to determine their *intrinsic* physical parameters by applying specific models, and trying to fit their SED. Results of the latter approach are reported here. We applied simple, one–zone, homogeneous models to all blazars strongly detected in the γ–ray band, assuming or not the presence of seed (for the inverse Compton process) photons produced outside the active region. Our results suggest that the SEDs of blazars are ruled by the amount of radiative cooling suffered by the electrons producing most of the emission. In turn, the amount of cooling is ruled by the amount of the external photon emission, which can be identified with radiation coming from the broad line clouds. Blazar SEDs are therefore organized in a sequence: objects with no or very weak emission lines (X–ray selected BL Lacs, or HBL) are characterized by very high electron energies and a Compton luminosity of the same order of the synchrotron one. These are TeV sources. BL Lacertae objects selected in the radio band (or LBL) are characterized by smaller electron energies, more total power and more line luminosity, and by a larger ratio of the Compton to synchrotron luminosity. They are GeV sources. Increasing the total intrinsic power and the line emission luminosity, we have smaller still electron energies (more cooling) and greater still Compton to synchrotron power ratio. These are flat spectrum radio quasars, with a high energy peak located at MeV–GeV energies.

1 Introduction

Blazars come in many flavours: the basic distinction among them is between lineless BL Lac objects and emission line flat spectrum radio quasars (FSRQ). There are overlaps, since the division line of a rest frame equivalent width of 5 Å of any emission line is crossed occasionaly by single objects. Examples are PKS 0537–441 (usually a BL Lac) and 3C 279 (usually a FSRQ, see Scarpa & Falomo 1997). BL Lac objects have been divided further into the subclasses of *high energy peak* (HBL) and *low energy peak* (LBL), according to their overall synchrotron spectrum, which has a peak in the EUV–soft X–ray band in the former objects and in the IR–optical band in the latter (Giommi & Padovani 1994). FSRQ have been instead

divided into the low polarization (LPQ) and high polarization (HQP) subclasses, according if the level of optical polarization is greater or smaller than 3%. HPQ are often identified with the *Optically Violent Variable* quasars (OVV), even if we know examples of LPQ which show rapid and strong variability. Also here there are overlaps, since the degree of polarization is extremely variable, and the classification may reflect an observational bias (for objects observed more frequently there are more chances to observe an high degree of polarization). In addition the contribution of the (probably thermal) blue bump component can dilute the non–thermal polarized emission, especially during faint states.

There is a general consensus upon the hypothesis that the extreme phenomenology which characterizes the non–thermal emission of blazars is due to bulk motion of the emitting plasma, flowing in a collimated jet. But differences in the bulk Lorentz factors Γ or viewing angle θ, alone, are not sufficient to explain the different characteristics between different subclasses, such as BL Lac objects and FSRQ. For instance, the idea that BL Lac objects are characterized by larger Γ and smaller θ, to let the non–thermal continuum swamp the lines and making the apparent superluminal velocities smaller than in FSRQ, leads to predict an average larger luminosity for these objects, contrary to what observed. Furthermore, estimates of $< \Gamma >$ for BL Lacs and FSRQ indicate that $< \Gamma >$ is larger in FSRQ (Madau Ghisellini & Persic, 1987, Ghisellini et al. 1993).

An attempt to unify HBL and LBL was made by Maraschi et al. (1986), Ghisellini & Maraschi (1989), Celotti et al. (1993), based on the observational evidence that the X–ray luminosity of both subclasses is, on average, the same; still, the X–ray surveys (which should therefore not be biased toward one particular class) found systematically HBL type objects. The idea was that the X–rays (thought to be synchrotron emission) were produced at the base of an accelerating jet, therefore in a zone where Γ is small, resulting in an emission more isotropically distributed that the optical or radio (coming further out along the jet). Therefore there should be a larger solid angle available for detecting BL Lacs in X–rays, the majority of which should be characterized by not strongly Doppler enhanced optical and radio emission, as observed. Unfortunately, this idea does not account properly for the (large) shift in the energy of the synchrotron peak, nor for the difference recently found between X–ray spectra: HBL tend to have steeper X–ray spectral indices than LBL, indicating that in the former class we see the steep tail of the synchrotron emission, while in the latter objects we see the flatter Compton component (see e.g., Comastri et al. 1995, 1997). Another evidence against the "accelerating jet model" is the variable and strong γ–ray emission detected in some BL Lacs: for the γ–ray to escape without suffering strong γ–γ absorption, we need large Γ even in the inner, X–ray emitting, jet (Dondi & Ghisellini, 1995).

Since blazar emission is beamed, there must be many sources, whose jet is pointed far from the line of sight, observed to have very different properties. These sources form the so–called "parent population" of blazars, whose identification is still under debate. The current understanding, after the work of Urry & Shafer (1984), Padovani & Urry (1992), Celotti et al. (1993), Maraschi & Rovetti (1994)

is that the BL Lacs 'live' in FRI radio–galaxies, while the more powerful FRII should host FSRQ (for a review, see Urry & Padovani 1995).

2 Gamma–loud blazars

The $\sim$60 blazars detected so far by EGRET (Fichtel 1994; von Montigny et al. 1995; Thompson et al. 1995) lead us to believe that the γ–ray emission is a characteristic of the entire blazar class. Blazars detected by EGRET (and by Cherenkov detectors, such as WHIPPLE and HEGRA, in the TeV band) include objects belonging to all different subclasses of blazars.

Only now we have the complete view of the overall emission of blazars, and for most sources only now we know in what band the 90% of the luminosity is emitted. Now we can model their SED for deriving the intrinsic physical parameters of the γ–ray emitting region, which dominates the bolometric output.

One is then driven to ask if the different subclasses in which we classify blazars are the result of some deeper physical distinction among them. In particular, there may exist one (or more) changing parameter determining the different properties (and classification) of blazars.

To investigate this problem, one can study the overall observed spectral properties of (relatively large) sample of blazars, to search for trends and/or correlations. This approach has been adopted by Fossati et al. 1997 (see also Fossati et al. this volume). Alternatively, one can try to model their emission in order to find the *intrinsic* values of the physical parameters, once beaming and relativistic effects are properly taken into account. This is the approach adopted in Ghisellini et al. (1997), whose results will be discussed here.

The first problem to face with this approach is the choice of the model, among the many already put forward to explain the entire SED of blazars. In the model of Mannheim (1993) shock–accelerated electrons and protons originate two different populations of emitting particles (electrons and electron–positron pairs), responsible of the entire SED of blazars by emitting synchrotron photons. In other models, instead, a single populations of electrons emits far IR (or even radio) to UV–soft X–ray radiation by synchrotron, and higher frequencies by the Inverse Compton process. Models of this kind differ by the adopted geometry (one–zone homogeneous models or inhomogeneous jet models), and by the nature of the target photons to be upscattered in energy by the Inverse Compton process. These photons could be synchrotron photons (Maraschi, Ghisellini, & Celotti, 1992; Bloom & Marscher, 1993) photons produced in the accretion disk (Dermer & Schlickeiser, 1993), or in the broad line region (BLR) illuminated by the disk (Sikora, Begelman & Rees, 1993, Blandford & Levinson, 1995), or self–illuminated by the jet (Ghisellini & Madau, 1996). Finally, target photons could be produced by a dusty torus surrounding the blazar nucleus (Wagner et al. 1995). These models have been applied to specific sources, and often more than one model could fit the same data (see von Montigny et al. 1997 for 3C 273, Ghisellini, Maraschi & Dondi 1996 for 3C 279, Comastri et al. 1997 for 0836+710).

Ghisellini et al. (1997) have chosen to apply two one–zone and homogeneous models: the synchrotron self–Compton (SSC) model and the "external Compton"

model (EC), in which the main contribution to the target photons is produced outside the γ–ray production region, by an (yet) unspecified mean. Data were collected from the literature for all the 45 blazars for which we have informations on their γ–ray spectral shape (to locate the energy of the peak of the high energy emission) and on their redshift (to measure the apparent luminosities). Among them there are 12 BL Lacs (4 HBL, 8 LBL), 15 LPQ, 15 HPQ and 3 FSRQ for which we do not have yet polarization measurements.

The model assumes that the emission region is a sphere of radius R, moving with a bulk Lorentz factor Γ at an angle $\theta \sim 1/\Gamma$ toward the observer. The magnetic field B is tangled and uniform, and the particle distribution is found solving the continuity equation, balancing continuous injection and radiative cooling. Pair production and Klein Nishina effects are taken into account. Electrons are injected with a power law distribution ($\propto \gamma^{-s}$) between γ_{min} and γ_{max}. In the simple case of Compton scattering in the Thomson regime and no pair production, the equilibrium distribution has a broken power law shape $\propto \gamma^{-2}$ for $\gamma < \gamma_b = \gamma_{min}$, and $\propto \gamma^{-(s+1)}$ above. γ_b is a crucial parameter, since it corresponds to the energy of those electrons responsible of both the synchrotron and the Compton peak. In the EC case, we further assume that the source is embedded in a photon bath of radiation energy density U'_{ext} (in the comoving frame), distributed in energy as a blackbody peaked at $\nu'_0 \sim 10^{16}$ Hz.

4 Results of fitting the SED of blazars

Fig. 1 shows some examples of the SED of BL Lacs and FSRQ, together with the fitting models. Note that, on the basis of the fit, one cannot discriminate between the SSC and the EC model. However, in the SSC case, we inevitably find large values of Γ, small values of the magnetic field and small synchrotron (intrinsic) powers. This implies that externally produced photons, not to contribute to the Compton process, must have a very small luminosity. This may be the case for *some* BL Lac, but it is certainly not for FSRQ, whose luminosity in the broad lines exceeds the found limit. Therefore in the following we concentrate on the discussion of the results of the EC fit for all sources. For *some* BL Lacs (e.g. 0235+164, 0537–441, 1604+159), some amount of external photons is indeed required to obtain a better fit, while for the remaining this can be taken as an upper limit not to worsen the fit.

4.1 Average values of the parameters

We require that the beaming factor (hence Γ) does not exceed a value of ~ 20, to be consistent with values of the observed superluminal velocities. The size R is constrained by the observed variability timescales, required not to exceed $\sim$1 day. Furthermore, the compactness corresponding to the injected power $\ell_{inj} = L_{inj}\sigma_T/(Rmc^3)$ is limited to values roughly less than unity, to avoid strong pair production.

With these constraints, we find that, on average, the size R is of the order of 10^{16}–10^{17} cm, the beaming factor $\delta \sim 15$, the magnetic field $B \sim 1$ Gauss and

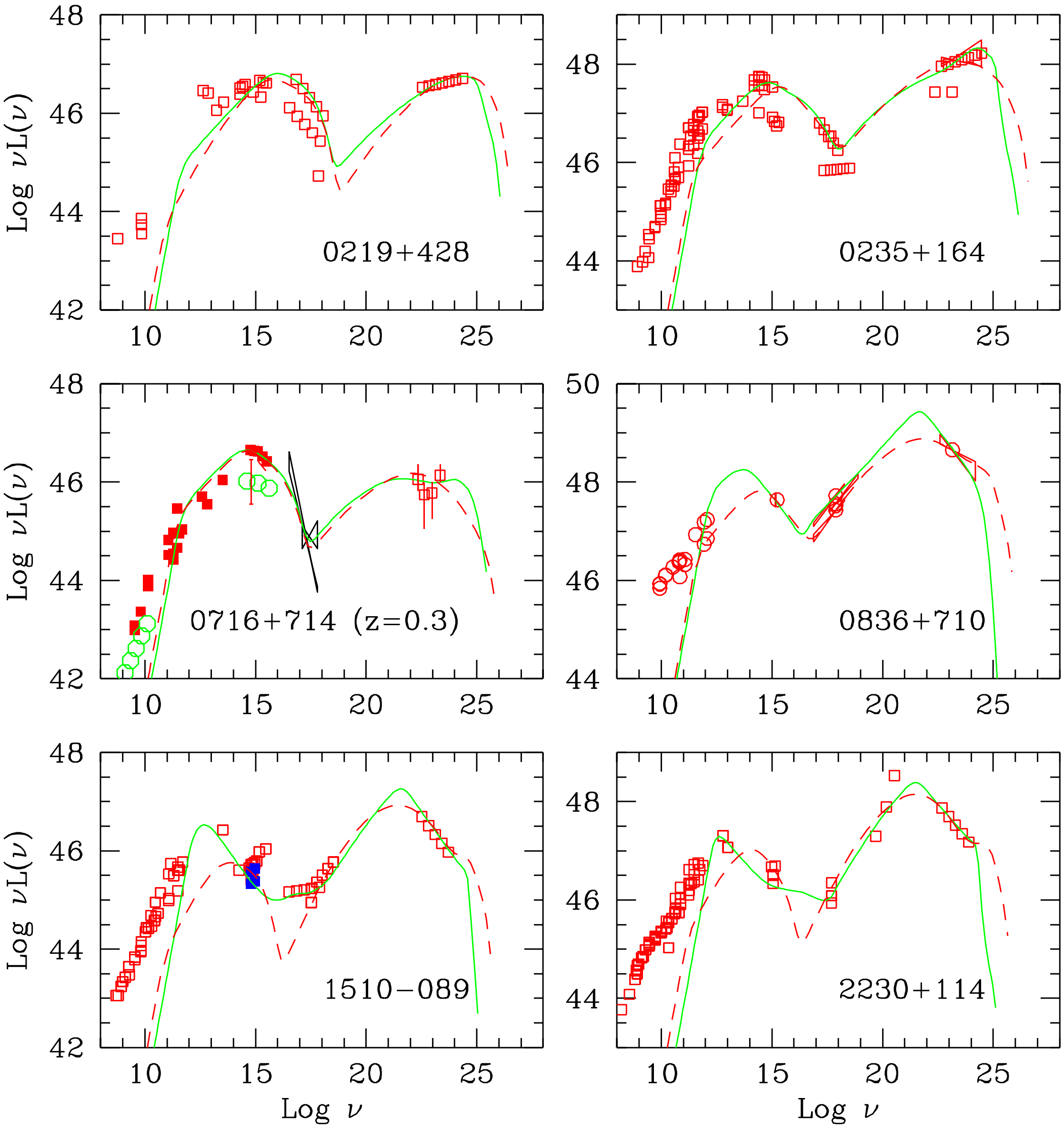

Fig. 1. Selected examples of SEDs of blazars, fitted by the SSC model (dashed line) and the EC model (solid line). 0219+428, 0235+164 and 0716+714 are BL Lac objects, while 0836+710, 1510–089 and 2230+114 are FSRQ. Adopted from Ghisellini et al. 1997.

the injected compactness $\ell_{inj} \sim 0.1$. The slope of the injected electron distribution is steep (s ∼2–3), making γ_{max} energetically unimportant. The most relevant parameter is γ_b (equal to γ_{min}, the miminum γ of the *injected* distribution), because it controls the locations of the synchrotron and Compton peaks. BL Lacs are characterized by larger values of γ_b than FSRQ.

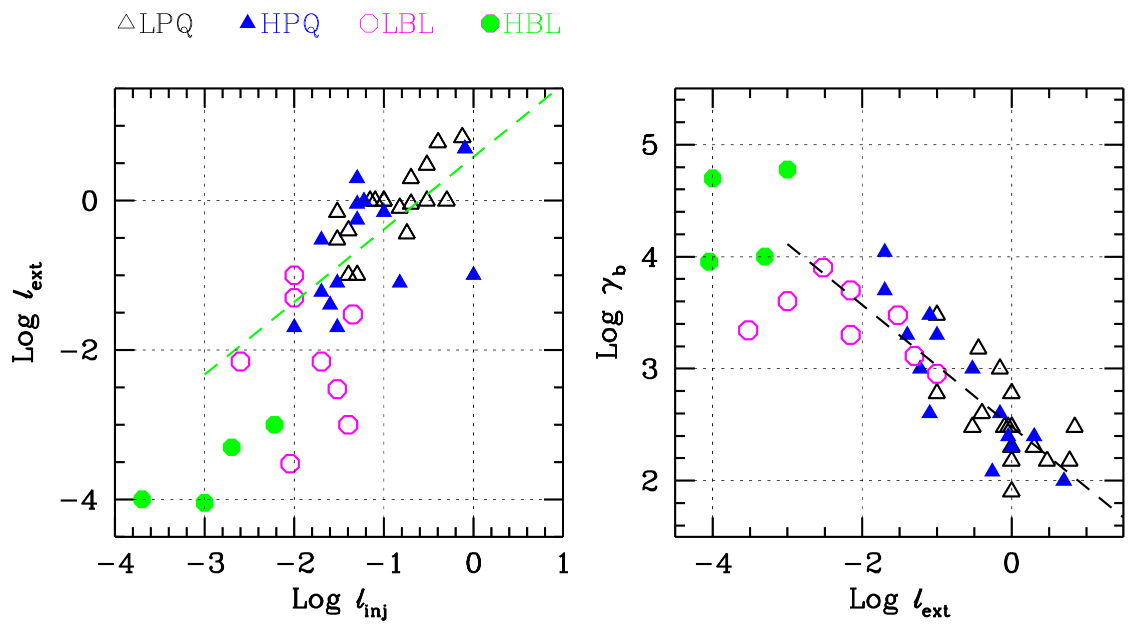

Fig. 2. *Left panel:* Correlation of the compactness ℓ_{ext} of external photons and the compactness injected in the source in the form of relativistic electrons. Both are intrinsic (comoving) quantities. *Right panel:* Correlation between the energy γ_b of the break in the electron distribution and ℓ_{ext}. Dashed lines are fits to the FSRQ only.

4.2 Correlations

Fig. 2a shows the correlation between the injected power and the amount of external photons (measured by an 'effective compactness' ℓ_{ext}: it is defined as if these photons were produced within the blob itself. In this way we can directly compare ℓ_{inj} and ℓ_{ext}). As can be seen, there is a strong correlation between the two (intrinsic) compactnesses. As expected, BL Lac objects lie on a separate portion of the plane: some LBL lie on the extrapolation of the correlation defined by FSRQ, while for HBL ℓ_{ext} is smaller.

Fig. 2b shows the correlation between γ_b and ℓ_{ext}. Also in this case there is a strong correlation: large values of ℓ_{ext} imply small value of γ_b, hence a synchrotron and Compton spectrum peaking at lower energies. Again, BL Lacs occupy a separate portion of the diagram, with HBL at one extreme.

Fig. 3 shows the correlations betwen γ_b and the total (intrinsic) amount of energy density, including radiation [both internal (produced by synchrotron) and external], and magnetic field. This is the strongest correlation we found. A linear correlation analysis (of the logarithm of the two quantities) yields $\gamma_b \propto U^{-0.6}$ and is shown by the dashed line.

Other important correlations found concern the 'Compton dominance' parameter L_c/L_s (ratio of the Compton to synchrotron luminosity) and either γ_b, or ℓ_{inj}, or ℓ_{ext}, in the sense that the L_c/L_s increases for larger ℓ_{inj} or ℓ_{ext}, and for smaller values of γ_b.

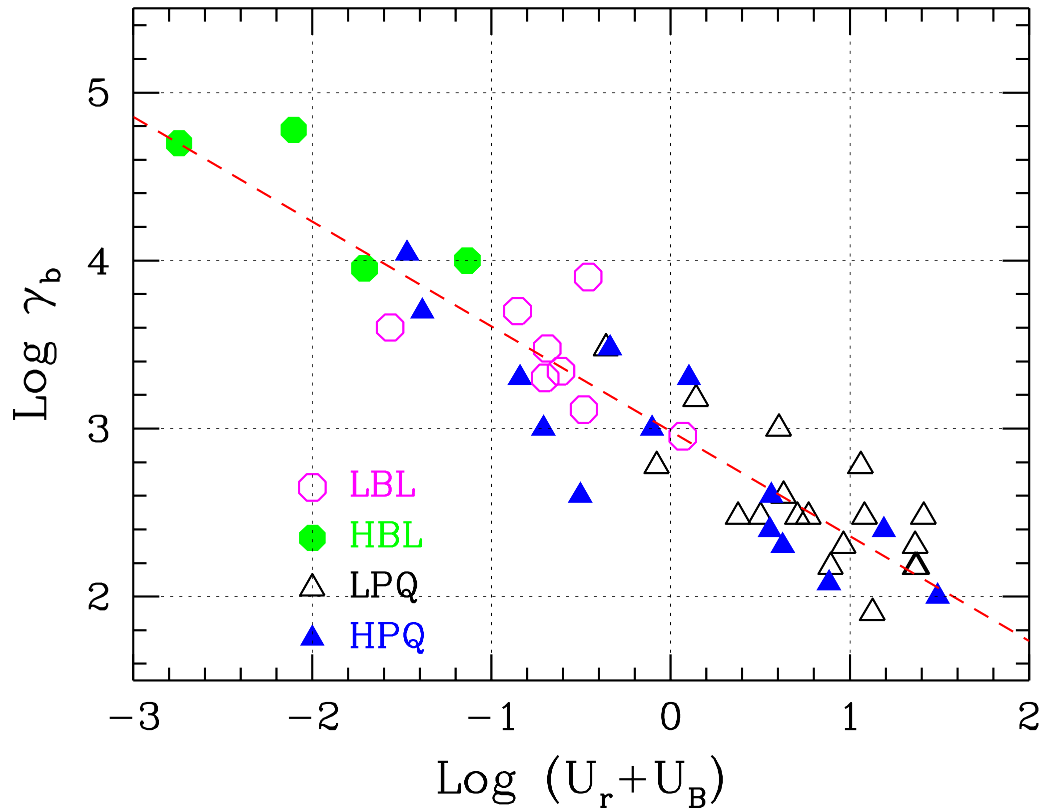

Fig. 3. Correlations between the value of the Lorentz factor of the electrons emitting at the peaks of the SED and the total energy density (radiative+magnetic).

4.3 Cooling vs acceleration

We can investigate further the found correlation between γ_b and U. Assume in fact that the (yet unknown) acceleration mechanism accelerates electrons up to some energy γ, where the cooling rate becomes competitive with acceleration. At this energy we then have $\dot\gamma_{cool} \sim \dot\gamma_{acc}$. Since $\dot\gamma_{cool} \propto \gamma^2(U_r + U_B)$, we have $\gamma_b = \mathrm{const} \times (\dot\gamma_{acc}/U)^{1/2}$. We then have (approximately) the correlation we found *if* $\dot\gamma_{acc}$ *is roughly constant.*

5 The blazar sequence

Our results indicate that all blazars can be organized in a well defined sequence, according to their intrinsic power, or the power in the external radiation field, as produced by the broad line clouds. This power increases from HBL to LPQ, which are at the extremes of the sequence. At the same time, the energy of the most relevant emitting electrons decreases, and the Compton dominance increases.

We then propose this scenario:

• HBL are characterized by the smallest intrinsic power, and by the weakest lines (and/or external radiation). Suffering less cooling, electrons can be accelerated at very high energies, enough to produce TeV emission by self–Compton emission, while their synchrotron spectrum peaks in the soft (or even hard) X–ray band. Their Compton dominance is at the low end of the blazar distribution.

• LBL are more powerful, and in some of them the external radiation field could be important. Radiative cooling is more severe, and electrons can attain smaller energies than in HBL. Correspondingly, the synchrotron peaks in the optical and the Compton emission peaks in the GeV band. Due to the increased (Compton) cooling, their Compton dominance is larger than in HBL.

• FSRQ are more powerful still, and their external radiation field is even more important, inducing a great radiative cooling. In this situation electrons can attain relatively small energies, and their synchrotron emission peaks in the IR, while the (dominating) Compton emission peaks in the MeV or in the MeV–GeV band.

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